EXPERIMENTAL LIGHT RAINFALL AND SNOWFALL PRODUCTS FOR CLOUDSAT

T. S. L'Ecuyer

Colorado State University, Fort Collins, Colorado 80523

ABSTRACT

When it launches next spring CloudSat, a component of the A-Train formation of satellites, will carry the first millimeter wavelength cloud radar in space. In addition to its stated objective of making a global survey of cloud microphysical properties, the CloudSat 94 GHz Cloud Profiling Radar (CPR) is also well-suited to the problem of determining the distribution of light rain and snow that can be difficult to detect using current space-borne instrumentation. This presentation will provide an overview of the CloudSat mission and describe two experimental precipitation algorithms being developed for retrieving light liquid rainfall and snow from CPR reflectivity observations. These algorithms have been applied to cloud radar data from the Advanced Microwave Scanning Radiometer (AMSR) validation experiment that took place in Wakasa Bay, Japan in 2003. While preliminary in nature, examples from this dataset illustrate the potential of CloudSat observations for studying the global distribution of drizzle, light rainfall, and snow. Ultimately, it is anticipated that CloudSat's experimental rainfall products may shed light on the importance of light rainfall and snow observations for establishing closure in the global energy budget and water cycle.

1. INTRODUCTION

Clouds and rainfall are central players in determining both the energy balance in the Earth's atmosphere and the global water cycle. They provide dynamic reservoirs for liquid and ice in the atmospheric branch of the hydrologic cycle, interact with both solar and terrestrial radiation, and determine the distribution of latent heat release to the atmosphere. As a result, clouds and precipitation represent an important factor impacting climate variability. To date, however, some of the more subtle details surrounding the conversion of cloud water to precipitation and the magnitude of the impact of changes in precipitation efficiency on large-scale circulation patterns have been difficult to quantify in part due to a lack of simultaneous, vertically-resolved cloud and precipitation microphysical property observations on global scales. The CloudSat Cloud Profiling Radar (CPR), the first millimeter wavelength radar to be flown in space, in concert with other sensors aboard the A-Train satellites will provide the first global survey of cloud vertical structure, light rainfall, and snowfall and their variability on synoptic and seasonal timescales providing a unique opportunity to study their role in global climate change. This paper provides an overview of the CloudSat mission and its role as a component of the multi-satellite, multi-sensor A-Train The estimation-based inversion framework that forms the basis of CloudSat's constellation. experimental light liquid precipitation and snowfall retrieval algorithms is described and examples of the application of these algorithms to airborne cloud radar observations are presented.

2. THE CLOUDSAT MISSION AND THE A-TRAIN

Shortly following its launch in April 2004, CloudSat will join Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and Aqua in a sun-synchronous orbit at an altitude of 705 km with an equatorial crossing time of 1:30 pm local time in the ascending mode of their orbits. These satellites and three others: Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar (PARASOL), Aura, and the Orbiting Carbon Observatory (OCO) will ultimately fly in formation providing an unprecedented view of our atmosphere. Fig. 1 presents a conceptual diagram of this constellation, nicknamed the ``A-Train" after its lead member, Aqua.



Figure 1: Conceptual diagram of the proposed A-Train constellation.

Also provided are the approximate equatorial crossing times for each satellite indicating their separation along the orbit. Until the launch of OCO in the more distant future, the Aqua satellite is the first in the A-Train carrying a variety of instruments for measuring the global distribution of water in all of its phases such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Microwave Scanning Radiometer (AMSR) for observing clouds and precipitation, respectively. Aqua also carries a Clouds and the Earth's Radiant Energy System (CERES) instrument for measuring top of the atmosphere fluxes. CloudSat and CALIPSO will fly in a tight formation closely behind Aqua crossing the equator approximately one minute later. Each carries an active sensor for measuring vertical profiles of clouds and aerosols. CloudSat and CALIPSO will be followed two minutes later by the PARASOL satellite providing polarized radiance measurements of clouds and aerosols and the Aura satellite with a payload devoted to determining the horizontal and vertical distributions of atmospheric pollutants and greenhouse gases. In the more distant future, the OCO satellite is expected to launch and join the front of the A-Train providing measurements of the global distribution of CO₂.

The over-arching goal of the A-Train constellation is to provide a synergistic view of the primary components of the global hydrologic cycle and energy budget including water vapor, clouds,

rainfall, aerosols, and the distribution of various chemical species in the atmosphere as well as longwave and shortwave radiative fluxes at the top of the atmosphere. At an orbit inclination of 98.2°, the A-Train observations will provide a dataset with which to study the interaction of these quantities on a global scale. CloudSat's primary role in the A-Train concept is to provide a vertical cross-section of liquid and ice water content and particle size by flying the first millimeter wavelength cloud radar in space (Stephens et al, 2002). The Cloud Profiling Radar (CPR) aboard CloudSat is a 94 GHz (3 mm wavelength) nadir-viewing radar with 500 m vertical resolution. At its altitude of 705 km the CPR will provide vertical profiles of radar reflectivity down to -26 dBZ at a spatial resolution of ~1.5 km. By virtue of this sensitivity, the CPR will simultaneously detect liquid clouds, ice clouds, light liquid rainfall, and snowfall as demonstrated by recent field campaigns such as CRYSTAL-FACE and the AMSR-E validation experiment at Wakasa Bay, Japan where airborne cloud radar data clearly depict examples of each. As a result, the products derived from these observations will offer insight into processes of fundamental importance to understanding the role of clouds and light precipitation in the large-scale environment. These products, in combination with those from other A-Train sensors, have the potential to both improve our ability to predict the weather as well as advancing our understanding of key climatic processes.

3. CLOUDSAT'S LIGHT RAINFALL AND SNOWFALL ALGORITHMS

The suite of algorithms developed for CloudSat have been designed to combine the CPR observations with complementary information from the other sensors across the A-Train, such as AMSR-E and MODIS radiance data from Aqua, to measure vertical distributions of liquid and ice water content in the atmosphere. In addition, CloudSat is dedicated to supplying rigorously-derived estimates of the uncertainties in each product. As a result, many of its algorithms have been formulated using the optimal estimation methodology described in Rodgers (2000). Within this framework, the most probable set of retrieval parameters is determined by minimizing the difference between a set of simulated measurements and observations subject to a desired set of *a priori* and observational constraints

$$\Phi = (\mathbf{x} - \mathbf{x}_a)^T \mathbf{S}_a^1 (\mathbf{x} - \mathbf{x}_a) + (\mathbf{y} - F(\mathbf{x}))^T \mathbf{S}_y^1 (\mathbf{y} - F(\mathbf{x})) + [(\sum \mathbf{x} - Z), \sigma_Z]$$

where **y** represents the vector of observed reflectivities, **x** is the vector of microphysical properties to be retrieved, and \mathbf{x}_a is an appropriate initial or *a priori* guess at the expected value of **x**. F(**x**) is a set of simulated reflectivities using our best understanding of the underlying physics relating the retrieval parameters to the observations. Z represents an integral constraint such as path-integrated attenuation (PIA) for precipitation retrievals.

Among the benefits of adopting the optimal estimation formalism is that it allows the formal inclusion of different forms of information including measurements from multiple sensors as well as *a priori* knowledge of the retrieval parameters. In addition, the technique provides a mechanism for explicitly specifying the uncertainties in all input data and assumptions in the forward model (i.e. through the error covariance matrices) weighting each piece of information accordingly. Finally, the technique provides a mathematical framework for propagating each of these individual sources of error through the retrieval process to yield quantitative measures of the uncertainty in each retrieval parameters. Specifically, the algorithms provide a retrieval error covariance matrix of the form:

$$\mathbf{S}_{x} = \left[\mathbf{S}_{a}^{-1} + \mathbf{K}^{\mathrm{T}}\mathbf{S}_{y}^{-1}\mathbf{K} + \frac{\mathbf{L}^{\mathrm{T}}\mathbf{L}}{\sigma_{Z}^{2}}\right]^{-1}$$

where the vector **L** consists of the derivatives of the constraint, Z, with respect to each retrieval parameter and the matrix **K** is the Jacobian of the forward model with respect to the retrieval vector, with elements given by $K_{ij} = \partial F_i / \partial x_j$.

This inversion approach forms the basis of CloudSat's experimental rainfall and snowfall algorithms. Due to the strong attenuation of precipitation-sized hydrometeors at 94 GHz, the rainfall algorithm requires an integral constraint in the form of either PIA or precipitation water path (PWP) to unambiguously retrieve rainfall rate. Thus the measurement vector, y, consists of the observed profile of CPR reflectivities while the constraint consists of the difference between the strength of the observed surface return and an estimate corresponding to clear-sky conditions. Appropriate uncertainties for each are determined through analysis of the sensitivities of the radar and radiative transfer forward models to assumptions such as the shape of the assumed drop size distribution and ambient temperature and humidity profiles. The algorithm, described in L'Ecuyer and Stephens (2002), proceeds by creating an initial profile of liquid and ice water content using Z-IWC and Z-LWC relationships. Attenuation is accounted for via corresponding k-Z relationships in a manner analogous to that of Hitschfeld and Bordan (1954). Below the melting level hydrometeors are assumed to follow a distribution of spherical liquid drops consistent with that introduced by Marshall and Palmer (1948) while those above are assumed to follow an equivalent distribution of ice spheres. The retrieval then iteratively minimizes the cost function using this initial profile for \mathbf{x}_{a} and the appropriate PIA estimate as a constraint. Mie theory is used to compute reflectivities and appropriate attenuation corrections for each layer to compare to the observed reflectivities in subsequent iterations.

Snowfall is common during the winter months at the mid and high latitudes that will make up a significant part of the A-Train orbit. CloudSat reflectivities will provide a means for detecting this snowfall and, when combined with the high frequency (89 GHz) channel of the Advanced Microwave Scanning Radiometer (AMSR) instrument aboard Aqua, may allow quantitative retrievals of falling snow. This possibility is also being explored using the optimal estimation approach described above. In this case, the CPR reflectivities are complemented with a high frequency microwave radiance observation to retrieve the width parameter and number concentration of an exponential distribution of spherical snow particles. The algorithm iteratively minimizes the cost function in much the same manner as the light rainfall algorithm, ultimately retrieving the vertical distribution of ice particle diameter and a column-mean number concentration that can be combined to estimate snowfall rate.

4. EXAMPLES

Preliminary versions of each algorithm have been applied to data acquired during the AMSR validation experiment that took place in Wakasa Bay, Japan during January and February, 2003. An example of a light liquid precipitation event that was observed by the Airborne Cloud Radar (ACR) during a single flight leg of the Wakasa Bay experiment is presented in Figure 2. The top left-hand panel presents observed reflectivities at 94 GHz. The second and third panels illustrate the method for deriving PIA based on the difference between the difference between the observed strength of the surface return (solid line) and an estimate of its strength under clear-sky conditions (dashed line). The lowest panel presents the estimated melting level determined from the vertical gradient of the observed reflectivity field.



Figure 2: Input fields (left) and results (right) of a sample application of CloudSat's experimental light rainfall algorithm to data acquired in the AMSR-E validation experiment that took place at Wakasa Bay, Japan in January and February, 2003. Left: Observed reflectivities and surface return are presented in the upper two panels followed by the estimated PIA and freezing level. Right: The upper two panels present retrieved liquid and ice water content and their uncertainties, respectively (note quantities pertaining to ice have been plotted as negative values to improve contrast) while the lower two panels present the retrieved near surface rainfall and its uncertainty, respectively.

The scene consists of a thick precipitating cirrus cloud overlying a persistent area of light rainfall indicated by a well-defined melting level at ~1.8 km. Reflectivities exceeding 10 dBZ throughout most of the scene indicate the presence of large precipitating liquid and ice particles and the decrease in reflectivity in the rainfall between the melting level and the surface is indicative of their strong attenuation at 94 GHz. Retrieved profiles of liquid and ice water content and surface rainfall rate for this case are presented on the right. Retrieved rainrates are typically less than 1 mm h⁻¹ across much of the flight line with the exception of three more intense rain shafts near the end of the leg. The corresponding PIA values range from 15-25 dB in these regions confirming the presence of more intense precipitation there (and constraining the retrieval accordingly). Fractional uncertainties in these quantities due to reflectivity and PIA measurement errors and uncertainties in assumed drop size distribution (DSD) are presented in the second and lowest panels.

An equivalent example of a snowing scene observed by the ACR ten days later is presented in Figure 3. The top two panels present reflectivities and corresponding 89 and 150 GHz brightness temperatures observed by the Millimeter-wave Imaging Radiometer (MIR) illustrating the characteristic shafts of falling snow and scattering of surface emission due to the large constituent ice particles. Profiles of retrieved width parameter, Λ , and column-mean number density, N₀, for the exponential particle size distribution, N(D) = N₀e^{- ΛD}, are presented in the third and fourth

panels of Figure 3. The largest particles are concentrated in the regions of strongest reflectivity as expected and these regions give rise to the largest snowfall rates as indicated in the bottom panel.



Figure 3: Example of a snowfall retrieval for a second set of observations from the Wakasa Bay experiment.

It is important to note that neither of these algorithms has undergone any formal validation but it is encouraging that the results are reasonable given the region and time of year. With the growing amount of available field data and the upcoming launch of CloudSat, extensive validation of both the rainfall and snowfall estimates and their uncertainty estimates are planned for the near future.

5. THE IMPORTANCE OF LIGHT RAINFALL AND SNOWFALL

Due to the strong absorption by raindrops at 94 GHz the CPR will suffer significant attenuation in rainfall. As a result, CloudSat's precipitation products will be physically limited to light rainfall and snowfall. This is, however, precisely the shortcoming of current satellite-based rainfall sensors that are primarily designed to measure moderate to heavy rainfall. There is little doubt that these heavier rainfall intensities make the largest contribution to the precipitation component of the global water cycle but there is evidence from ground-based observations that light precipitation events may make a non-negligible contribution, particularly at high latitudes. Furthermore, light precipitation events are typically more frequent and exhibit larger spatial coverage than heavier events and play a more significant role in modifying global energy balance. Schumacher and

Houze (2000) explore the amount of precipitation missed by the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) using ground-based radar observations obtained at Kwajalein Island in the Tropical West Pacific. They found that 46% of the raining area observed by the local ground radar between January 1998 and August 1999 fell below the 18 dBZ threshold of the PR accounting for 2.3% of the total rain accumulation. The significance of these results depends on the application. Missing 46% of the raining area has serious implications for representing the radiative impacts of these systems. Hydrologic applications, on the other hand, may not suffer greatly from missing 2.3% of the total accumulation.

The radar data acquired during the TRMM-Large-scale Atmosphere Biosphere (TRMM-LBA) field experiment that took place in central Brazil echo these results. Figure 4 presents histograms of observed surface reflectivity plotted in terms of frequency of observations (left) and total rainfall (right). Reflectivity values below the minimum detectable signal of the TRMM PR are shaded in gray to indicate the events that would escape detection. Once again, the results indicate that more than half of all raining pixels have reflectivities below the 18 dBZ threshold but that these pixels only account for 3% of the total rainfall in the region. It is important to note, however, that both Kwajalein Island and the Amazon are characterized by distinctly tropical rainfall systems. It is anticipated that both the frequency and the rainfall contribution of light rainfall systems increases substantially at higher latitudes.



Figure 4: Histograms of reflectivity observations acquired during the TRMM-LBA field experiment that took place in the Amazon in January and February 1999. The number of pixels with the corresponding reflectivity bin is depicted on the left while the right presents the contribution of each reflectivity bin to the total rainfall observed during the field campaign. The shaded region illustrates the pixels that fall below the sensitivity of the TRMM PR.

By virtue of its lower reflectivity factor and variable particle shapes snowfall presents an even greater problem to current active and passive satellite-based sensors. Falling snow is virtually invisible to these sensors yet it can represent a significant hydrologic source at high latitudes as evidenced by Figure 5. The plot on the left presents the annual mean precipitation across Canada between 1951 and 1980 while the one on the right indicates the fraction of this precipitation that falls in the form of snow. Using basic assumptions regarding particle density and fall speed, it is easy to show that, in terms of accumulation, the TRMM PR would miss approximately 37% of the frozen precipitation that falls in Montreal, Quebec, 67% of that falling in Prince Albert, Saskatchewan, and 85% of that falling in arctic regions. One would expect similar results to apply in northern Europe and Asia.



Figure 5: Annual mean precipitation across Canada (left) and the fraction of this precipitation that falls in the form of snow (right) (courtesy: Meteorological Service of Canada).

CloudSat's sensitivity will make it an ideal instrument to detect and possibly quantify the amount of light rainfall and snowfall that falls around the globe. In this way CloudSat may provide a means for establishing the amount of light rain missed by current satellite-based rainfall sensors and provide the first global survey of frozen precipitation. While the importance of these forms of precipitation on global scales is currently unknown, it is clear from the examples presented above that they are relevant in many regions. In fact, CloudSat's contribution to global precipitation observations may ultimately be to shed light on exactly this issue, i.e. to answer the question: How important are light rainfall and snow in the global energy budget and hydrologic cycle?

6. REFERENCES

Hitschfeld, W. and J. Borden, 1954: Errors inherent in the radar measurement of rainfall at attenuating wavelengths, *J. Appl. Meteor.* **11**, 58-67.

L'Ecuyer, T. S. and G. L. Stephens, 2002: An estimation-based precipitation retrieval algorithm for attenuating radars, *J. Appl. Meteor.* **41**, 272-285.

Marshall, J. S. and W. H. Palmer, 1948: The distribution of raindrops with size, *J. Meteor.* **5**, 165-166.

Rodgers, C. D., 2000: <u>Inverse methods for atmospheric sounding</u>. <u>Theory and practice.</u>, World Scientific, Singapore, 2000.

Schumacher, C. and R. A. Houze, Jr., 2000: Comparison of radar data from the TRMM satellite and Kwajalein oceanic validation site, *J. Appl. Meteor.* **39**, 2151-2164.

Stephens, G. L. and co-authors, 2002: The CloudSat mission and the A-Train: A new dimension of space-based observations of clouds and precipitation, *Bull. Amer. Meteor. Soc.* **83**, 1771-1790.